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Hydrologic reinforcement induced by contrasting woody species during summer and winter

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Abstract

Aims Vegetation can improve slope stability by transpiration-induced suction (hydrologic reinforcement). However, hydrologic reinforcement varies with seasons, especially under temperate climates. This study aims to quantify and compare the hydrologic reinforcement provided by contrasting species during winter and summer.

Methods One deciduous (*Corylus avellana*) and two evergreens (*Ilex aquifolium* and *Ulex europaeus*) were planted in 1-m soil columns. Soil columns were irrigated, left for evapotranspiration and then subjected to extreme wetting events during both summer and winter. Soil water content, matric suction and strength were measured down the soil profile. Plant water status and growth (above- and below-ground) were also recorded.

Results The tested species showed differing abilities to remove water, induce suction and hence influence soil strength. During summer, only *Ulex europaeus* provided a soil strength gain (up to six-fold the value at saturation) along the entire depth-profile inducing high suction (e.g. 70 kPa), largely maintained after wetting events in deeper soil (0.7 m). During winter, the evergreen species could remove water but at slower rates compared to summer.

Conclusions Evergreens could slowly induce suction and hence potentially stabilise slopes during winter. However, there were large differences between the two evergreens because of different growth rate and resource use.

Keywords: Eco-engineering; Evergreens; Hydrologic reinforcement; Matric suction; Transpiration

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Introduction

The use of vegetation to stabilize and increase resilience of natural and man-made slopes is a cost-effective and environmentally-friendly solution when compared to traditional engineering methods (Stokes et al. 2014). Vegetation can stabilize slopes providing "hydro-mechanical reinforcement", which can be defined as the gain in soil shear strength due to the combined mechanical effects of plant root anchorage (aka mechanical reinforcement) and hydrologic effects of soil drying by plant transpiration (aka hydrologic reinforcement). While the former reinforcement mechanism has been well recognised in the last decades (De Baets et al. 2008; Liang et al. 2015; Stokes et al. 2014), the latter has received increasing attention in the research of soil bio- or eco-engineering in recent years (Gonzalez-Ollauri and Mickovski 2017; Kim et al. 2017; Leung et al. 2017; Leung and Ng 2013; Rahardjo et al. 2014; Sidle and Bogaard 2016; Veylon et al. 2015). As plants transpire, soil drying increases soil matric suction and hence soil strength due to the increase in effective stress (Simon and Collison 2002). Moreover, the presence of vegetation can affect soil hydrology and hence slope stability by (i) intercepting rainfall that would otherwise infiltrate in the soil (Gonzalez-Ollauri and Mickovski 2017; Keim and Skaugset 2003), (ii) modifying soil subsurface flow (Ghestem et al. ; 2011; Leung et al. 2015a) and (iii) altering soil water retention properties (Bengough 2012; Leung et al. 2015b). Although soil hydrology is known to affect the stress state of unsaturated soil and the tendency for slopes to fail (Ching-Chuan et al. 2009; Rahimi et al. 2011; Sidle and Bogaard 2016), the effects of hydrologic reinforcement, especially when coupled with plant characteristics, has been poorly investigated compared to root mechanical reinforcement (Stokes et al. 2014).

Recent studies have highlighted that transpiration-induced matric suction could provide a greater soil-strength gain than that of root inclusions (Kim et al. 2017; Pollen-Bankhead and Simon 2010; Simon and Collison 2002; Veylon et al. 2015). The comprehensive study performed by Kim et al. (2017) investigated the inter- and intra-annual variation of both hydrologic and root mechanical reinforcement under different climates and vegetation types. Hydrologic reinforcement provided by woody plants exceeded mechanical reinforcement from 121 to 365 days per year, contributing to an additional factor of safety (FoS: ratio of resisting and driving forces acting on a slope) of more than 0.3. However, the intra-annual contribution of hydrologic reinforcement to slope stability is strongly dependent on climate. In subtropical climate regions, such as Laos, hydrologic reinforcement provided the greatest contribution to the slope FoS for almost all of the year. On the contrary, highly seasonal rainfall in tropical climate (e.g. Costa Rica) and low evaporative demand in temperate climate during winter (e.g. France) caused large intra-annual variations in hydrologic reinforcement. Similar observations were reported for a vegetated slope in Hong Kong (with subtropical to tropical climate), where rainfall in the wet season caused the dissipation of matric suctions in the top 2.5 m of a slopes soil with positive pore pressure values up to 25 kPa, although during antecedent dry season the matric suction (i.e. negative pore pressure) in the root zone reached a steady-state between 160 and 190 kPa (Leung and Ng 2013). Simon and Collison (2002) quantified the seasonal variation of hydrologic reinforcement in relation to different vegetation types (woody species and erosion-control grasses). Their slope stability analysis shows that woody species induced the greatest increase of FoS due to greater transpiration. Moreover, the weaker hydrologic effect of erosion-control grasses was explained by their late recovery after winter.

In temperate climates, as highlighted by Kim et al. (2017), the potential benefits provided by transpiration are generally negligible during winter periods when reinforcement is most critical for slope stability. Indeed, in temperate regions landslides are normally triggered during autumn and winter rainy seasons when soils are typically near field capacity and evapo-transpiration is minimal (Sidle and Bogaard 2016). Limited studies in temperate climates have mainly investigated the effect of deciduous species, which start to transpire in late spring (Gonzalez-Ollauri and Mickovski 2017; Pollen-Bankhead and Simon 2010; Simon and Collison 2002). Simon and Collison (2002) suggest that evergreens (conifers) may provide hydrologic reinforcement during winter/spring period, but this hypothesis has not yet been tested. Although it is already well-known that different plant functional types (i.e. deciduous and evergreens) could have significantly different water uptake during seasons (Baldocchi et al. 2010; Baldocchi et al. 1987; Ellsworth and Sternberg 2015), we did not find any study that compared the hydrologic reinforcement provided by deciduous and evergreen species during summer and winter. Indeed, data on the interplay between different plant types and hydrologic reinforcement over time are severely lacking, and it remains an area where fundamental research is urgently needed. This has also been highlighted by Stokes et al. (2014), who review some key issues and challenges that eco-engineering researchers and practitioners are facing. Eco-engineer's decisions on species selection are seldom made with optimisation of slope hydrologic reinforcement in mind, and the extent of variation among species is often unknown. In particular, there is a lack of ground truth data for several species of eco-engineering interest.

This study extends our previous research (Boldrin et al. 2017), where we investigated the relation between plant traits and hydrologic reinforcement during the establishment of ten different woody species widespread in Europe. In the present study, we selected three representative yet contrasting species and developed a much more complex and controlled experimental system to study more factors. These include the effects of season (i.e. summer vs winter), plant functional types (i.e. deciduous vs evergreen) and soil depth on the magnitude of suction and soil strength induced by transpiration and then preserved after extreme wetting events. The objective of this study is to quantify and compare the hydrologic reinforcement provided by transpiration of contrasting species (e.g. deciduous and evergreen) during winter and summer. We hypothesize that (i) evergreens transpiration can affect hydrologic reinforcement during winter period and (ii) adaptive strategies of species can drive hydrologic reinforcement during both summer and winter. The experiments reported in this study tested these hypothesis using a deciduous species (*Corylus avellana*) and two contrasting evergreen species (*Ilex aquifolium* and *Ulex europaeus*), which are wide spread in Europe and adapted to the temperate climate.

Methods

Selected plant species

Three woody species, *Corylus avellana* L., *Ilex aquifolium* L. and *Ulex europaeus* L., were selected for testing in this study (Table 1). These species are widely spread in Europe and correspond to distinct plant functional types (i.e. deciduous and evergreens). Species were selected because of their contrasting ability to remove water shown in a recent study that

compares the hydrologic reinforcement provided by ten European woody species (Boldrin et al. 2017a). We selected three species out of ten because some species in Boldrin et al. (2017a) have shown similar hydrologic reinforcement such as *Buxus sempervirens* and *Ilex aquifolium* or *Cytisus scoparius* and *Ulex europaeus*. Hence, it was more useful to select the three most representative yet contrasting species for more detailed investigation, comparison and discussion in this study. Moreover, these species have also been quantified mechanically for root mechanical reinforcement (Bischetti et al. 2005; Boldrin et al. 2017b; Norris et al. 2008). In particular, *U. europaeus* was recently chosen by Liang et al. (2017) as a model species to study the effects of root mechanical reinforcement on slope stability in a geotechnical centrifuge. All plants were supplied by Coles Nurseries (Leicester, UK) as potted plants. The original growing medium (compost) was carefully washed away from the root system of each plant before transplanting into soil columns.

Table 1 A list of three woody species selected for testing in this study

Species	Family	Common name	Functional type	Acronym
Corylus avellana L.	Betulaceae	Hazel	deciduous	Ca
Ilex aquifolium L.	Aquifoliaceae	Holly	evergreen	Ia
Ulex europaeus L.	Fabaceae	Gorse	evergreen	Ue

Soil columns

Plastic drainage pipes (150 mm inner diameter and 1.2 m long) were used for plant growth. The pipes were lined with a 0.2 mm thick polythene sheet to facilitate the extraction of the entire soil columns at the end of experiment. The base of each pipe was covered with a nylon mesh (1 mm aperture) and an overlying layer of pea gravel (50 mm thick), to facilitate drainage. The agrarian top-soil used in this study was sampled from Bullionfield, The James Hutton Institute, Dundee, UK. It was a sandy loam, which comprised of 71% sand, 19% silt and 10% clay contents (Loades et al. 2013). The soil (sieved < 10 mm; water content 0.18 g g^{-1} (determined by standard Proctor test)) was packed in 11 layers to obtain a 1.05 m soil column with an initial dry density of 1300 kg m^{-3}. Plunger compaction plate was used which had a thin outer ring protruding from the surface to compact the soil greater and hence limit root growth in the interface between soil and pipe in accordance with Mickovski et al. (2009). During soil packing, the surface of each layer was abraded to achieve a better contact between each successive layer. A 100 mm-tall pipe edge was maintained to favour irrigation. The water release curve of the packed soil is reported by Boldrin et al. (2017a). The theoretical available water content (i.e. the difference between the water content at field capacity (5 kPa matric suction) and the water content at the permanent wilting point (1500 kPa matric suction; Kirkham 2005) of the soil was 0.14 g g^{-1}.

Following packing a bare root plant was transplanted into the top 150 mm of the soil and then the soil was re-packed carefully around the root system. Four replicates of each species were prepared (i.e. 12 planted soil columns in total). After transplanting, *C. avellana* and *I. aquifolium* plants were pruned to 0.65 m-height. Three fallow soil columns were used as control. The soil surface of each column was covered with a 10 mm-thick pea gravel layer

to minimize soil evaporation and soil disturbance due to irrigation. Note that the drying of soil surface induced by evaporation was not of interest for this study, whose objective is to quantify hydrologic reinforcement induced by transpiration of contrasting species. Moreover, evaporation generally affects only soil surface and hence its contribution to slope stabilisation is negligible. All soil columns were randomly arranged in an unheated glasshouse with no additional light or heat provided. The glasshouse temperature was thus close to the outdoor temperature during the entire study. All soil columns (i.e. vegetated and fallow) were subjected to the same irrigation schedule ranging from 35 to 90 mm per week. The amount of water per week (e.g. 35 or 90 mm) aimed to avoid any form of water stress (i.e. water was supplied *ad libitum*) for all tested species. Immediately after irrigation water content ranged between 0.20 and 0.25 g g^{-1}. Note that no irrigation was provided during experimental phases (see below). Glasshouse air temperature (˚C) and relative humidity (%) were recorded at hourly intervals (OM-EL-2 data logger, Omega Engineering, UK). OM-EL-2 data logger had an accuracy of ± 0.5 ˚C and ± 3.5 % for temperature and relative humidity, respectively. Incoming solar radiation (W-m^2) was recorded by the meteorological station of The James Hutton Institute.

Measurements of soil water content and matric suction

After initial plant establishment, water content sensors (Theta Probe ML2X connected to DL6 loggers, Delta-T devices, Cambridge, UK) were installed at 100 mm depth (vertically installed from soil surface) and 300 mm depth (horizontally installed through pipe wall) to record water content at hourly intervals. The sensors were calibrated in the laboratory using identical soil and installation procedure in the glasshouse. The calibration equations for the vertically-installed (Eq. (1)) and horizontally-installed (Eq. (2)) sensors can be expressed as:

$$w = 0.0140 + 0.0003 * V \quad (1)$$

$$w = 0.0288 + 0.0003 * V \quad (2)$$

where w is water content (g g^{-1}) of soil and V the reading of Theta Probe in millivolts.

Miniature tensiometers (SWT-5 connected to DL6 logger, Delta-T devices, Cambridge, UK) were horizontally installed at 0.1, 0.3 and 0.7 m below the soil surface, each through a 6.5 mm diameter hole predrilled in the pipe wall.

To assess the water removing ability of the three different species during different seasons (i.e. summer vs. winter), all 12 planted soil columns and three fallow soil columns were irrigated until the soil was close to saturation, as indicated by 0 kPa of matric suction recorded by tensiometers at each of the three depths. Each soil column was then left for evapo-transpiration (planted pots) and evaporation (fallow pots) until suction values were close to the tensiometer limit of 80 kPa. Subsequently, all soil columns were subjected to two consecutive ponding events of 16 mm each for less than five min to simulate extreme wetting events (Ng et al. 2013). Indeed, in less than five minutes, soil was subjected to an amount of water equivalent to the weekly rain (16 mm) during winter (≈ average weekly rain for

Dundee area during December – January (1971 – 2000)). Identical procedures were performed in both summer (August 2016) and winter (January – February 2017).

Soil penetration resistance

Soil penetration resistance (MPa) tests were performed in each soil column using a portable penetrometer (Basic Force Gauge, Mecmesin, UK; cone diameter of 2.96 mm and cone angle of 30˚) to quantify the hydrologic reinforcement to the soil due to transpiration-induced suction (Boldrin et al. 2017a; Weaich et al. 1992). Soil penetration resistance has been shown to correlate with transpiration-induced suction (Boldrin et al. 2017a) and has been used to evaluate the mechanical or hydrologic reinforcement provided by vegetation (Boldrin et al. 2016; Boldrin et al. 2017a; Meijer et al. 2016; Osman and Barakbah 2006; 2011). To allow for the penetration tests, 3.1 mm diameter holes were drilled in the pipe wall prior to each test. Maximum soil resistance was determined by horizontally penetrating the cone to 35 mm into the soil. Note that maximum penetration resistance is always higher (e.g. + 30 or 40 %) of average penetration resistance of soil. The measurements were taken at 0.1, 0.3 and 0.7 m below soil surface for each soil column at different times after summer and winter soil saturation events.

Plant water status

To assess the plant water status of the tested species, pre-dawn (Ψ_{pd}) and minimum (Ψ_{min}) plant water potentials (MPa) were measured (Scholander et al. 1965; Tyree and Hammel 1972) using a pressure chamber (Plant Moisture System, Skye Instruments, UK). Measurements were performed, during both summer and winter, on a sunny day after soil saturation and when soil columns showed an evident water content reduction (i.e. two times per season). Ψ_{pd} and Ψ_{min} were measured on twigs (i.e. terminal branches) sampled before 07:00 h and between 12:30 and 13:30 h (UK local time), respectively. A black polythene canopy was used to maintain dark condition and hence to avoid transpiration during the summer twig sampling for Ψ_{pd}. The canopy was removed immediately after sampling. At least one twig per plant was randomly collected and immediately wrapped in a cling film and inserted in a plastic bag. The samples were briefly stored in a refrigerated cool bag before being transported to the laboratory for pressure chamber testing.

Measurement of above- and below-ground plant growth

Initial above-ground biomass was evaluated on four replicate plants per species in June 2016. These plants had the same origin, age and height of plants growing in the soil columns after transplanting. Final above-ground biomass of plants growing in all planted soil columns was measured after one year following measurements of initial biomass (June 2017). Biomass was quantified through oven drying at 70 °C until a constant weight was obtained. In June 2017, planted soil columns were removed from pipes and sectioned into five sections corresponding to depth ranges (0 – 0.15 m; 0.15 – 0.25 m; 0.25 – 0.50 m; 0.50 – 0.75 m; 0.75 – 1.05 m). Roots in each section were washed from the soil in gently running tap water on a set of sieves with a range of sieve sizes from 2.0 to 0.5 mm mesh (Smit et al. 2000). Sampled

roots were stored at 5 ˚C in sealed bags with wet blotting paper before further material processing (e.g. root scanning, oven-drying). Representative subsamples (22 ± 2 % of root dry mass per soil depth ranges) of roots in each section were scanned and analysed using WinRhizo (Regent Instruments Inc.) to determine total root length and root length per diameter classes (0.1 m interval width; roots from < 0.1 to 5 mm). Measured length and dry mass of root subsamples were used to obtain the specific root length (SRL, root length by mass; m g^{-1}). The total root length in each section was then estimated by multiplying the dry root biomass by the SRL. Thicker roots (> 5 mm diameter), if present, were processed and analysed separately to avoid overestimation of root length. Root length density (RLD; cm cm^{-3}) was obtained by dividing the total root length by the volume of each soil section.

Statistical analysis

Statistical analysis was performed using GenStat 17th Edition (VSN International) and SigmaPlot13 (Systat Software Inc). Significant differences were assessed with one way-ANOVA, followed by post hoc Tukey's test. Data that did not follow a normal distribution were square-root or log-transformed prior to ANOVA. Repeated measures of water content during progressive soil drying were tested for significant differences between treatments using Residual Maximum Likelihood (REML) with first order auto-regression as model for correlation within subject across time and uniform correlation within subjects. Square-root transformed matric suction and log-transformed penetration resistance were analysed using Generalized Linear Models (GLM) with normal distribution and identity link function. Species and soil depth were included as fixed factors to assess differences in matric suction and interactions among factors. When analysing penetration resistance, treatment, soil depth and season were kept as fixed factors. Data recorded at soil saturation were not included in the GLM analysis of penetration resistance. χ^2 (chi-square; Wald statistic) and corresponding *p*-value are given for GLM analysis. Significance of correlations established in this study was tested by regression analysis and Spearman's rank correlation. In addition to equations of fitted curve and coefficient of determination (R^2) obtained from regression analysis, r and the corresponding *p*-value from Spearman's rank correlation analysis are given in Table 2. Results were considered statistically significant when p-value ≤ 0.05. The variability of averaged data is expressed as ± standard error of mean.

Results

Glasshouse environmental conditions

Temperature and relative humidity recorded in the glasshouse during summer (15th - 29th Aug 2016) and winter (11th Jan - 20th Feb 2017) phases of experiment highlighted distinct weather conditions between these two periods (Fig. 1 a and b). Mean daily temperature and relative humidity over the summer phase averaged 19.0 ± 0.5˚C and 69.6 ± 1.8 %, respectively. During winter phase, temperature and relative humidity averaged 5.7 ± 0.4 and 85.9 ± 1.0, respectively. During both summer and winter, indoor glasshouse conditions (e.g. temperature) were close to and representative of outdoor conditions in the UK. During the summer phase, the meteorological station at The James Hutton Institute, situated a few

hundred meters from our glasshouse, recorded average daily temperature and relative humidity of 14.8 ± 0.2 ˚C and 84.0 ± 1.1 %, respectively. During the winter phase, daily temperature and relative humidity recorded by the meteorological station averaged 4.4 ± 0.5 ˚C and 86.8 ± 1.0 %, respectively. Incoming solar radiation during summer phase (160 ± 14 W-m^2; daily average during experimental period) was five-times greater than that recorded during the winter phase (32 ± 3 W-m^2; Fig. 2). Incoming solar radiation showed maximum values up to 740 W-m^2 (13:00; 17th Aug 2016) and 406 W-m^2 (12:00; 20th Feb 2017) during summer and winter phases, respectively.

Soil water content and matric suction

During the summer phase, the monitoring of soil water content (*w*) after saturation showed significant differences (*p*-value < 0.001) between treatments at both 0.1 and 0.3 m in soil columns (Fig. 3 a and b). At 0.1 m depth from the soil surface, water content in fallow soil columns did not drop below 0.21 g g^{-1} and generally remained close to the field capacity value of 0.25 g g^{-1} (Boldrin et al. 2017a) during the entire period (i.e. 14 days). At the same depth, all three species showed similar abilities to remove water with average water content values on day 11 (before ponding) ranging from 0.12 (in *C. avellana*) to 0.14g g^{-1} (in *I. aquifolium* and *U. europaeus*; Fig. 3 a). The ponding on days 11 and 14 caused an abrupt increase in water content within all soil columns (Fig. 3 a). However, the average water content in the planted soil (0.21 ± 0.01 g g^{-1}) was drier than in the fallow soil (0.25 ± 0.01 g g^{-1}). The driest value after the two ponding events was recorded in *U. europaeus* soil (i.e. 0.17 g g^{-1}). Note that water content among planted soil columns showed no statistical difference after the extreme wetting events (ponding events).

At 0.3 m soil depth, three distinct patterns of water content could be identified (Fig. 3 b). In fallow soil columns, water content did not drop below the field capacity value of 0.25 g g^{-1} during the entire period (i.e. 14 days). On the contrary, water content in *C. avellana* and *U. europaeus* consistently decreased to 0.13 ± 0.01 and 0.14 ± 0.00 g g^{-1}, respectively. *I. aquifolium* showed a limited ability to remove water at 0.3 m depth when compared with the two other species ($w \geq 0.21$g g^{-1}). Ponding events did not notably affect water content at 0.3 m depth in both *C. avellana* and *U. europaeus* soil columns.

During the winter phase, soil water content (Fig. 4 a and b) highlighted a significant difference among treatments at both depths (*p*-value = 0.004 at 0.1 m; *p*-value < 0.001 at 0.3 m). At 0.1 m depth (Fig. 4 a), water content recorded in *C. avellana* soil column did not differ from the fallow. Only the evergreens *I. aquifolium* and *U. europaeus* reduced soil water content when compared to the fallow treatment. Indeed, water content in *I. aquifolium* and *U. europaeus* soil was, respectively, 0.04 and 0.07 g g^{-1} lower than the value (0.22 g g^{-1}) recorded in both the fallow soil and *C. avellana* soil on day 39 (Fig. 4a). At 0.3 m depth, only *U. europaeus* soil columns showed a constant rate of water uptake (approximately 0.01 – 0.02 g g^{-1} per week; Fig. 4 b). While the ponding events at 0.1 m increased the water content back to the initial values close to the field capacity on day 41 (Fig. 4 a), only a small water content increase was measured at 0.3 m depth in *U. europaeus* soil columns, where water content remained lower compared with the other treatments (day 41 Fig. 4 b). It should be noted that the two ponding events (16 mm + 16 mm) determined a notable and similar water

increase at 0.1 m during both summer and winter. After the summer ponding events, the soil water content at 0.1 m increased by an average 0.06 ± 0.01 g g^{-1} (C = 0.03 ± 0.00; Ca = 0.09 ± 0.01; Ia = 0.07 ± 0.01; Ue = 0.06 ± 0.01 g g^{-1}). Similarly, after the winter ponding events the soil water content increased by an average 0.05 ± 0.01 g g^{-1} (C = 0.03 ± 0.01; Ca = 0.03 ± 0.00; Ia = 0.06 ± 0.00; Ue = 0.07 ± 0.00 g g^{-1}). Therefore, the water content increase following the ponding events was consistent during summer and winter with the exception of the deciduous *C. avellana*, which had a pre-ponding water content close to field capacity during the entire winter phase.

Matric suction, recorded at different soil depths, was consistent with water content measurements during both summer and winter phases (Figs. 3, 4, 5 and 6). During summer, all three species were able to induce a quick increase of matric suction, which reached values up to 70 kPa (day 11; Fig. 5 a). On the contrary, in fallow soil columns, matric suction did not exceed 5 kPa during the entire summer phase (Fig. 5 a, b and c). The three woody species highlighted a different ability of inducing matric suction in soil profile. Indeed, we found a significant difference among species (statistically tested on day 11; χ^2 = 25.7; *p*-value < 0.001) and a significant interaction between species and soil depth (χ^2 = 476.6; *p*-value < 0.001). At 0.7 m depth, only *U. europaeus* was able to induce matric suction (Fig. 5 c), which on day 11 (71 ± 2 kPa) was 35-fold greater than in the other treatments (matric suction ≤ 2 kPa). The effect of ponding on matric suction strongly depended on soil depth. Indeed, after ponding, no statistical difference was found among treatments in shallow soil (i.e. 0.1 m). In contrast, high matric suction (e.g. > 60 kPa in 0.7 m *U. europaeus*) was maintained in deeper soil depth (i.e. 0.3 and 0.7 m depth; Fig. 5 and Suppl. Fig. 1 b) after ponding, as well as significant difference among treatments.

During winter, only evergreen species were able to increase matric suction in soil columns (Fig. 6). However, the rate of the increase of matric suction was much smaller compared with the summer case. High matric suction (> 60 kPa) was found only in *U. europaeus* shallow soil 37 days after soil saturation (Fig. 6 a). Matric suction measured in *I. aquifolium* did not exceed 30 kPa during the overall winter phase and was limited to the shallow soil (i.e. 0.1 m). Only *U. europaeus* increased matric suction at 0.3 and 0.7 m depth, where values up to 62 and 22 kPa were measured, respectively. Upon ponding, the suctions in the shallow soil (0.1 m) of all treatments were lost (values ≤ 5 kPa). In contrast, matric suctions of 31 ± 12 and 14 ± 4 kPa were retained at 0.3 and 0.7 m in *U. europaeus* soil columns, respectively (Fig. 6 b and c).

Soil strength

Soil penetration resistance varied significantly with treatment (χ^2 = 219.0; *p*-value < 0.001), soil depth (χ^2 = 103.3; *p*-value < 0.001) and season (χ^2 = 36.1; *p*-value < 0.001), which highlighted a significant interaction (treatment*depth*season: χ^2 = 61.6; *p*-value < 0.001), when tested by the generalized linear models. Linear correlations between matric suction and soil penetration resistance highlighted the hydrologic reinforcement induced by plant water uptake (Fig. 7). In fallow soil columns, both penetration resistance and matric suction remained small at all three depths for both summer and winter cases (Fig 7 a, b and c). On the contrary, in planted soil columns, penetration resistance changed notably with both soil depth

and season. In particular, penetration resistance values recorded in *C. avellana* soil showed significant seasonal difference (*p*-value < 0.001). While the penetration resistance during summer varied between 1.9 and 7.1 (0.1 and 0.3 m depth), during winter this did not exceed 1.9 MPa (Fig. 7 d and e; Fig. 8 a and b). *U. europaeus* provided a soil strength gain along the entire soil column (Fig. 7 j, k and l; Fig. 8). During summer, after 11 days of transpiration, the penetration resistance at 0.1, 0.3 and 0.7 m of *U. europaeus* soil was respectively 6.1 (4.68 ± 0.86 MPa), 5.4 (2.63 ± 0.52 MPa) and 4.0-fold (2.18 ± 0.32 MPa) greater than the values recorded immediately after soil saturation (Fig 8 a). During winter, the soil strength gain was smaller and mainly in shallow soil (Fig. 8 c), where the ponding events caused an abrupt reduction in strength (Fig. 8 d). However, the strength gain by transpiration before ponding was maintained at 0.3 and 0.7 m depth, where penetration resistance values were significantly higher than those recorded during saturation (Fig. 8 c and d). At saturation, the penetration resistance highlighted a statistical difference between treatments only in shallow soil depth (i.e. 0.1 m; *p*-value = 0.04). However, no significant differences between treatments were observed at deeper depths (0.3 and 0.7 m) at saturation (Fig. 8).

Table 2

Summary of fitted curves (Matric suction vs. penetration resistance; Fig. 7), R^2 for fitted curves (regression analysis), r and the corresponding *p*-value from Spearman's rank correlation analysis. n.s. indicates the lack of significant relation between the two variables

Treatment	Fitted curve Matric suction vs. penetration	R^2 of fitted curve	r (Spearman's rank correlation)	*p*-value (Spearman's rank correlation)
Control 0.1 m	f=0.06*x+0.22	0.41	0.61	0.002
Control 0.3 m	-	-	-	n.s.
Control 0.7 m	-	-	-	n.s.
***C. avellana* 0.1 m**	f=0.05*x+0.76	0.80	0.77	< 0.001
***C. avellana* 0.3 m**	f=0.05*x+0.65	0.65	0.81	< 0.001
***C. avellana* 0.7 m**	-	-	-	n.s.
***I. aquifolim* 0.1 m**	f=0.04*x+0.52	0.75	0.89	< 0.001
***I. aquifolim* 0.3 m**	-	-	-	n.s
***I. aquifolim* 0.7 m**	-	-	-	n.s.
***U. europaeus* 0.1 m**	f=0.05*x+0.76	0.65	0.90	< 0.001
***U. europaeus* 0.3 m**	f=0.03*x+0.78	0.51	0.76	< 0.001
***U. europaeus* 0.7 m**	f=0.02*x+0.87	0.57	0.83	< 0.001

Plant water status

The measurements of plant water status provided insights into the water removing ability of the three contrasting species. Plant water potential, Ψ, was assessed on days characterized by different soil water contents (Fig. 9) during the winter phase in January – February 2017 and also in June 2017, which had consistent weather conditions (temperature: 17.0 ± 0.3 ˚C; RH: 70.0 ± 0.8%) with the summer phase in August 2016. During the winter phase, both evergreen species showed a small difference (≤ 0.2 MPa) between the minimum water potential (Ψ_{min}) and the pre-dawn water potential (Ψ_{pd}; Fig 9 a and b). Both water potentials did not exceed 0.6 MPa, suggesting large soil water availability during the entire winter period. On the contrary, during summer, plant water status showed large changes and

differences among species (Fig. 9 c and d). Two days after saturation, Ψ_{pd} did not differ among species (≈ -0.3 MPa), implying an equal soil water status and hence water availability in all columns (Fig. 8 c). On the same day, Ψ_{min} measurements highlighted a strong decrease (i.e. becoming more negative) of water potential (difference between Ψ_{min} and Ψ_{pd} up to 0.9 MPa) with Ψ_{min} values up to -1.2 MPa (*C. avellana*). After 16-days of evapotranspiration following soil saturation, Ψ_{pd} of *U. europaeus* exceeded -1.5 MPa (i.e. permanent wilting point for mesophytic plants) and the value was significantly different (p-value < 0.001) when compared with *C. avellana* and *I. aquifolium* Ψ_{pd} (Fig. 9 d).

Plant growth

The increase in above-ground biomass per year ranged between 35% (*I. aquifolim*) and 175% (*U. europaeus*) (Fig. 10). Only *C. avellana* and *U. europaeus* highlighted a significant increase of biomass (p-value < 0.001; *I. aquifolium* biomass difference: p-value = 0.11).

One year after planting, we found an increase of root depth in all three species (Fig. 11 a, b and c). In particular, all root systems of four *U. europaeus* replicates reached the gravel at the bottom of soil columns (> 1.0 m depth). Most of the replicates of *C. avellana* (3/4) reached the bottom layers of soil (> 0.75 m depth). However, the root system of this species highlighted an exponential decrease of both biomass and root length density with depth (Fig. 11). *I. aquifolium* showed a relatively smaller root growth in depth, which did not exceed 0.5 m depth. Root length (%) per diameter classes down soil profile is given for each species in Suppl. Fig. 2.

Discussion

Our test results showed remarkable differences among the three tested species in terms of water removing ability and hence hydrologic reinforcement in the soil profile during summer and winter months (Figs. 3, 4 and 7). The study of plant water relations (Fig. 9) and development, both above- and below-ground (Figs. 10 and 11), indicates that the water removing ability of these species was mainly associated with the growth rate of plant shoot and root.

During summer, all three species were able to induce matric suction and hence provide soil hydrologic reinforcement. Matric suction values greater than 60 kPa were recorded in the shallow soil of all planted soil columns (Fig. 5 a), whereas in fallow soil suction did not exceed the field capacity value (≈ 5 kPa) for the entire monitoring period. This highlighted that in absence of transpiration, drainage and evaporation could induced no or minimal suction, despite favourable conditions such as a relatively free draining soil with small compaction (i.e. soil bulk density ≈ 1300 kg m^{-3}), high temperature and low relative humidity (Fig. 1 a). However, it should be noted that the repacked nature of our soil (no macro-pore network) might have limited preferential pathways for water and hence drainage. The three tested species have very different water uptake abilities, which represented the main driver of soil strength gain (i.e. penetration resistance; Figs. 7 and 8). On the contrary, we observed a small contribution of root mechanical reinforcement to strength gain only in shallow soil (i.e. 0.1 m). Indeed, at saturation when hydrologic reinforcement was absent (see the oblique line patterns in Fig. 8), the penetration resistance in all treatments was close to the

values (≤ 1MPa) recorded in the control fallow soil columns without roots. This implies that mechanical root reinforcement contributed only little to the measured penetration resistance.

While *I. aqufolium* provided hydrologic reinforcement mainly in shallow soil, *U. europaeus* induced significant hydrologic reinforcement in the entire soil profile. *C. avellana* on the other hand showed an intermediate behaviour. These differences can be mainly explained by the root development in depth (Fig. 11). Although all plants were transplanted at the same soil depth (0.15 m), after one year rooting depth between species was different. The root system of greatest extent was that of *U. europaeus*, which explored the entire soil volume from surface to base. Canadell et al. (1996) reviewed rooting depth from 290 observations of maximum rooting depth for 253 woody and herbaceous species and found maximum rooting depth ranging from 0.3 m for tundra species to 68 m for *Boscia albitrunca* in the central Kalahari. In all ecosystems, 90 - 95% of roots were found within 2 m from the soil surface, where most of the nutrients reside. Deep roots comprise only a small fraction of the root system, but often have water transport conduits with much larger diameters and, therefore, higher root hydraulic conductivity compared with shallow roots or stems (McElrone et al. 2004). Rooting depth is a key factor that controls the amount of plant hydrologic and mechanical reinforcement provided to soil (Ghestem et al. 2014; Leung et al. 2017; Ng et al. 2013; Stokes et al. 2009). While rainfall-induced landslides are normally shallow (< 1 – 1.5 m deep) and generally of small volume on steep soil slopes of 30 - 50°, deep-seated landslides are sometimes reported (Zhang et al. 2011). In deep soil, mechanical reinforcement is generally minimal as root density decreases rapidly with increasing depth (e.g. root length density of *C. avellana* Fig. 11 d). However, hydrologic reinforcement could still contribute to slope stability (Kim et al. 2017; Ng et al. 2016; Shao et al. 2017; Sidle and Bogaard 2016). In particular, matric suction could be maintained (i.e. residual suction) even during and after extreme wetting events in deep soil (i.e. 0.7 m) but quickly disappeared in shallow soil (Fig. 5 and 6; Suppl. Fig. 1). This observation is in accordance with previous studies (Ng et al. 2016; Ng et al. 2013; Pollen-Bankhead and Simon 2010). In the field, mature trees could develop persistent suctions that are maintained over a period of years or even decades because the rate of rainfall infiltration from the soil surface in winter periods was insufficient to re-wet the deep soil (Briggs et al. 2013; Smethurst et al. 2015). Therefore, residual suction can be maintained in both fine-grained soil (Smethurst et al. 2015) and in coarse-grained soils as observed in this and previous studies (Ng et al. 2016; Ng et al. 2013; Pollen-Bankhead and Simon 2010), if sufficient matric suction is generated in deep soil by plant transpiration. In temperate regions at high latitudes (e.g. United Kingdom), preserving residual suction (hence strength) in deep soil during extreme rainfall events will have a major role in slope stabilisation under climate change. Indeed, precipitation has been increasing in the British Isles over the last decades and climate model simulations for the 21st century are consistent with projecting precipitation increases in high latitudes (IPCC 2013). For instance, during the wet winter 2015, rainfall exceeded 150 mm per day (e.g. 405 mm on 4 - 5 December in Cumbria, UK), resulting in severe and extensive flooding and slope instability across UK (Online documents 1 and 2).

During winter, deciduous *C. avellana* did not affect soil hydrology, as expected (Fig. 4 and 6). On the contrary, evergreen species highlighted slow water removal and increase of matric suction. During this period, suction increased at a much smaller rate compared with

summer. While in summer, high matric suction values (> 60 kPa) were recorded after 8 days since soil saturation, in winter these values were measured only in *U. europaeus* shallow soil after 37 days since soil saturation. Despite slow increase of matric suction, it translated in a proportional increase of soil strength (Figs. 7 and 8). This much slower increase of suction is likely related to both environmental conditions (i.e. evaporative demand) and plant physiology. Indeed, vapor pressure deficit (VPD; calculated from average temperature and relative humidity) and solar radiation (daily average), which are the main driving forces of transpiration (Fletcher et al. 2007; Jones 2013; Pieruschka et al. 2010), were approximately five-fold smaller during winter phase (VPD = 0.13 kPa; solar radiation = 32 W-m^2) compared with summer (VPD = 0.67 kPa; solar radiation = 160 W-m^2). Moreover, low and sub-zero temperatures during winter (e.g. night of day 16; Fig. 1b) may have led to xylem embolism and decrease of hydraulic conductance of evergreens (Lee et al. 2004; Sperry and Sullivan 1992). Indeed, water in xylem generally freezes between 0 and -2˚C and after embolism water transport takes place at a very low rate (around 3% of normal rates; Lambers et al. 2008, Sperry and Sullivan 1992). Moreover, the transpiration-induced suction during winter was mainly achieved in shallow soil (i.e. 0.1 m). Our test results show that seven-fold greater values were recorded at 0.1 m compared with 0.7 m deep soil (Fig. 6 day 37, *U. europaeus*). We hypothesise that the deeply-rooted *U. europaeus* has a dual or dimorphic root system, which allows for a shift between shallow root water uptake during wet seasons (i.e. winter), and deep-penetrating root water uptake during dry seasons (i.e. summer; Dawson and Pate 1996; Ellsworth and Sternberg 2015; Wang et al. 2017). Evergreens with dimorphic root system may be suitable for eco-engineering use as they may induce greater suction in deep soil and maintain it during wet season when the hydraulic conductivity in shallow soil may be decreased by transpiration induced-suction.

We acknowledge that soil columns are a simpler system compared with natural and made-made slopes, where slope angle, horizontal fluxes, pore network (i.e. preferential flows) and root architecture (e.g. roots growing up- or down-hill) can affect soil hydrology and hence slope stability (Ghestem et al. 2011; Sidle and Bogaard 2016). Moreover, soil columns can confine horizontal root growth. However, the use of soil columns provides information and results which cannot be obtained in the field due to the high variability and several technical limitations. Indeed, soil columns and boxes of similar size or smaller have been used to investigate plant-induced suction (i.e. hydrologic reinforcement; Boldrin et al. 2017; Garg et al. 2015a; b; Gonzalez-Ollauri and Mickovski 2017; Ng et al. 2016; Ng et al. 2013; Pollen-Bankhead and Simon 2010) and root mechanical reinforcement (Liang et al. 2017; Loades et al. 2010; Mickovski et al. 2009), deriving insightful results in the context of soil bioengineering. Testing using soil columns can never represent complex field conditions, but it does provide a simplified and less-variable controlled experimental system.

The measurements of plant water status (i.e. plant water potential) provide insights into the water removing ability of the three tested species. Indeed, the pre-dawn (Ψ_{pd}) and minimum (Ψ_{min}) water potential (Fig. 9) were consistent with the summer and winter matric suction changes in soil columns (Figs. 5 and 6). In particular, during the winter phase, both evergreen species showed a small difference ($\leq$ 0.2 MPa) between Ψ_{min} and Ψ_{pd} (Fig 9 a and b), thus indicating a small water potential gradient driving the water uptake across the soil-plant-atmosphere continuum (Matzner and Comstock 2001; Nardini et al. 2003; Steudle

2000; 2001; Steudle and Peterson 1998), as Ψ_{pd} and Ψ_{min} indicate the plant water status in absence of transpiration (i.e. at equilibrium with soil water status) and the plant water status during transpiration, respectively (see below). On the contrary, in summer, the difference between Ψ_{min} and Ψ_{pd} (i.e. $\Delta\Psi$) was up to 0.9 MPa (e.g. *C. avellana* Fig. 9 c).The large $\Delta\Psi$ and hence transpiration recorded in *C. avellana* two days after soil saturation (Fig 9 c) may explain the steeper increase of matric suction driven by this species during the summer phase (Fig. 5 a, days 1 - 2; (Matzner and Comstock 2001). Ψ_{pd} variation during progressive soil drying showed typical decrease (becoming more negative) pattern (Lebourgeois et al. 1998; Schmidhalter 1997). In fact, Ψ_{pd} could reflect the water potential of soil profile (related to matric suction) explored by functional roots. Hence Ψ_{pd} may be a valid surrogate of direct measures of soil matric suction, as plants tend to establish equilibrium overnight with wetter zones of bulk soil acting as a "living tensiometer" (Bucci et al. 2009; Faiz 1983; Jones 2007; Schmidhalter 1997). However, our Ψ_{pd} measures might provide only relative information on soil-plant water status. Indeed, it should be noted that the assumption of a correspondence between soil matric suction and plant Ψ_{pd} may not always be correct when large matric potential range are considered. For example, plants subjected to drought can efficiently control plant water potential by stomatal closure (Bates and Hall 1981; Jones 1983). Moreover, drought may not allow sufficient recovery of plant water potential overnight due to increased soil-root hydraulic resistance and xylem cavitation (Schmidhalter 1997). Therefore, further research is needed to assess the potential use of plants as living tensiometers in eco-engineering, in particular species-specific effects (e.g. isohydric vs. anisohydric species (Tardieu and Simonneau 1998) should be considered.

The two tested evergreens, *I. aquifolium* and *U. europaeus*, highlighted remarkable differences in terms of both hydrologic reinforcement of soil profile (Fig. 7) and plant growth (Figs. 10 and 11). These results are in accordance with the previous findings by Boldrin et al. (2017a). Indeed, Boldrin et al. (2017a) identified two distinct evergreen behaviours in terms of (i) small (e.g. *Buxus sempervirens* and *Ilex aquifolium*) and (ii) large (e.g. *Cytisus scoparius* and *Ulex europaeus*) hydrologic reinforcement during a short-term summer experiment. In a temperate climate, evergreen habit is generally a morpho-physiological adaptation that aims at a slow-return of energy investment and hence resource conservation (Aerts 1995; Givnish 2002; Wright et al. 2004). Indeed, evergreen tissues, both leaves and roots, have a longer lifespan and hence slower overall nutrient loss rate compared with deciduous tissues (Aerts 1990; 1995; Aerts and Van Der Peijl 1993; Escudero et al. 1992). This adaptation strategy is particularly advantageous in soils characterized by low nutrient availability. However, in general evergreen traits (e.g. small specific leaf area) are negatively associated with plant growth rate and transpiration (Reich et al. 1999). Hence, deciduous species could outperform evergreens in nutrients-rich soils (Aerts 1995). It may be hypothesised that the observed differences between *I. aquifolium* and *U. europaeus* (i.e. small vs. large hydrologic reinforcement; Fig. 7) are the results of different plant-nutrient economies. *I. aquifolium* has a nutrient conservation strategy and hence a slow growth rate (Figs. 10 and 11) as do most temperate evergreens. On the contrary *U. europaeus* had a fast relative growth rate (i.e. very competitive; Figs. 10 and 11) and strong hydrologic reinforcement down the entire soil profile (Figs. 7 and 8), which may be explained by its nitrogen fixation strategies and hence lack of nitrogen (i.e. nutrient) limitation for growth and

physiological processes (Cavard et al. 2007; Reid 1973). Note that root nodules were clearly observed on the root systems of our *U. eurepaeus* plants. Indeed, *U. europaeus* has a nitrogen fixation rate of about 70% (nitrogen derived from the atmosphere) and is capable of fixing up to 200 kg ha^{-1} yr^{-1} of nitrogen (Cavard et al. 2007; Egunjobi 1969). Therefore, *U. europaeus* is less dependent on soil nitrogen and does well in nutrient-poor and highly disturbed soils. The dry matter production rate by this species could be up to 15 t ha^{-1} per year (Clements et al. 2001). Nitrogen is a key factor for photosynthesis and transpiration (Brown 1978; Evans 1989; Grassi et al. 2005; Niinemets et al. 2015; Sinclair and Horie 1989). For example, N-supplied plants have more efficient water use, characterized by fast transpiration in relatively wet soil (Shimshi 1970). Another possible reason for the relatively weak hydrologic reinforcement of *I. aquifolim* (compared to *U. europaeus*) may be attributable to its hydraulic architecture, characterized by small lumen of xylem conduits (Martínez-Vilalta et al. 2002) as previously discussed in Boldrin et al. (2017).

Because of the very different behaviour among evergreen species not all evergreens will necessarily provide stronger hydrologic reinforcement than deciduous species for soil eco-engineering purposes. Indeed, as far as fast establishment (i.e. high plant growth rate) and hydro-mechanical reinforcement are concerned, ecological engineers should consider the selection of nitrogen fixing evergreens such as *U. europaeus* and avoid "resource-saver" evergreens like *I. aquifolium*. Furthermore, the pioneering ability of *U. europaeus* in colonising highly disturbed soils fulfils the environmental (e.g. initiation of natural succession and biodiversity increase) and practical requirements of eco-engineering, such as rapid growth on degraded land (Norris et al. 2008).

Conclusions

Tested species, *C. avellana*, *I aquifolium* and *U. europaeus*, exhibited contrasting hydrologic reinforcement down the soil profile. While *I. aqufolium* provided hydrologic reinforcement mainly in shallow soil (i.e. no deeper than 0.1 m depth), *U. europaeus* induced greater hydrologic reinforcement in the entire soil profile down to 0.7 m depth. Moreover, the matric suction, induced in deeper soil, could be maintained (i.e. residual suction) during and after extreme wetting events but quickly disappeared in shallow soil. Differences in hydrologic reinforcement were mainly explained by the rooting depth of each species. During winter, evergreen species had a much slower water uptake rate and smaller increase in matric suction compared with summer. Despite their slow increase of matric suction during winter, the magnitude of suction was much higher than the value recorded in deciduous soil columns, thus providing greater increases of soil strength. The two evergreens, *I. aquifolium* and *U. europaeus*, exhibited striking differences in hydrologic reinforcement of the soil profile and plant growth rate. As far as fast establishment and hydro-mechanical reinforcement are concerned, the nitrogen-fixing *U. europaeus*, may be a more suitable candidate for soil eco-engineering purposes than the "resources saver" evergreen *I. aquifolium*

This study was performed under semi-controlled environmental conditions, where water input was manipulated. Further work is needed to improve the understanding of the effects of different plant functional types and seasons on hydrologic reinforcement of slopes under field conditions. On-going field experiments on a marginally-stable vegetated

610 embankment in an uncontrolled environment are being conducted to validate the findings
611 presented in this study.

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878 **Figure captions**

879 **Fig. 1** Average daily temperature (solid line - closed symbols) and average daily relative
880 humidity (open symbols - dashed line) recorded in the glasshouse during the summer (a) and
881 winter (b) phases of the study. Means are reported ± standard error of mean (24 h)

Fig. 2 Average daily incoming solar radiation recorded by the meteorological station of The James Hutton Institute during the summer (a) and winter (b) phases of the study. Means are reported ± standard error of mean (24 h)

Fig. 3 Monitoring of water content in control and vegetated soil columns at 0.1 (a) and 0.3 (b) m depths between August 15th (soil saturation) and August 30th, during progressive soil drying since soil saturation in summer. Water content recorded at 13:00 is reported per day. On day 11 (August 26th) and day 14 (August 29th) since soil saturation, soil columns were irrigated with 16 mm of water (ponding events). Acronyms: C: fallow soil (control); Ca: *C. avellana* vegetated soil; Ia: *I. aquifolium* vegetated soil; Ue: *U. europaeus* vegetated soil. Means are reported ± standard error of mean (n of C soil columns= 3, n of Ca, Ia and Ue soil columns= 4)

Fig. 4 Monitoring of water content in control and vegetated soil columns at 0.1 (a) and 0.3 (b) m depths between January 11th (soil saturation) and February 24th, during progressive soil drying since soil saturation in winter. Water content recorded at 13:00 is reported per each day. On day 40 (February 20th) and day 41 (February 21st) since soil saturation, soil columns were irrigated with 16 mm of water (ponding events). Acronyms: C: fallow soil (control); Ca: *C. avellana* vegetated soil; Ia: *I. aquifolium* vegetated soil; Ue: *U. europaeus* vegetated soil. Means are reported ± standard error of mean (n of C soil columns= 3, n of Ca, Ia and Ue soil columns= 4)

Fig. 5 Matric suction recorded in control and vegetated soil columns at 0.1 (a), 0.3 (b) and 0.7 (c) m depths between August 15th (soil saturation) and August 29th, during progressive soil drying since soil saturation in summer. On day 11 (August 26th) and day 14 (August 29th) since soil saturation, soil columns were irrigated with 16 mm of water (ponding events). Acronyms: C: fallow soil (control); Ca: *C. avellana* vegetated soil; Ia: *I. aquifolium* vegetated soil; Ue: *U. europaeus* vegetated soil. Means are reported ± standard error of mean (n of C soil columns= 3, n of Ca, Ia and Ue soil columns= 4)

Fig.6 Matric suction recorded in control and vegetated soil columns at 0.1 (a), 0.3 (b) and 0.7 (c) m depths between January 11th (soil saturation) and February 21st, during progressive soil drying since soil saturation in winter. On day 40 (February 20th) and day 41 (February 21st) since soil saturation, soil columns were irrigated with 16 mm of water (ponding events). Acronyms: C: fallow soil (control); Ca: *C. avellana* vegetated soil; Ia: *I. aquifolium* vegetated soil; Ue: *U. europaeus* vegetated soil. Means are reported ± standard error of mean (n of C soil columns= 3, n of Ca, Ia and Ue soil columns= 4)

Fig. 7 Soil penetration resistance plotted against matric suction. Closed, open and x symbols represent data recorded during summer, winter and at saturation, respectively. a) Fallow control soil columns at 0.1 m depth; b) Fallow control soil columns at 0.3 m; c) Fallow control soil columns at 0.7 m; d) *C. avellana* soil columns at 0.1 m depth; e) *C. avellana* soil columns at 0.3 m depth; f) *C. avellana* soil columns at 0.7 m depth; g) *I. aquifolium* soil columns at 0.1 m depth; h) *I. aquifolium* soil columns at 0.3 m depth i) *I. aquifolium* soil columns at 0.7 m depth j) *U. europaeus* soil columns at 0.1 m depth; k) *U. europaeus* soil

columns at 0.3 m depth; l) *U. europaeus* soil columns at 0.7 m depth. Fitted curves and 95% confidence bands are shown in graphs. Summary of fitted curves is given in Table 2

Fig. 8 Soil penetration resistance recorded in control and vegetated soil columns at 0.1, 0.3 and 0.7 m depth on a) Day 11 summer phase (August 26th); b) Day 13 winter phase (January 24th); c) Before ponding on day 37 winter phase (February 17th) and d) After ponding on day 41 winter phase (February 21st). Oblique line pattern indicates the penetration resistance of soil recorded at saturation (matric suction < 2 kPa). Means are reported ± standard error of mean. Different letters indicate significant penetration resistance difference among treatments (C: fallow soil (control); Ca: *C. avellana* vegetated soil; Ia: *I. aquifolium* vegetated soil; Ue: *U. europaeus* vegetated soil), as tested by one-way ANOVA followed by post hoc Tukey's test. * indicates a significant difference of penetration resistance compared with the values at saturation. Non-normally distributed data were log or square root transformed in the statistical analysis

Fig. 9 Pre-dawn (Ψ_{pd}) and minimum (Ψ_{min}) water potential measured in twigs of *C. avellana* (Ca), *I. aquifolium* (Ia) and *U. europaeus* (Ue) on (a) 12th January 2017 (1 day after soil saturation); (b) 17th February 2017 (37 days after soil saturation); (c) 31st May 2017 (2 days after soil saturation) and 15th June 2017 (16 days after soil saturation). Water content at 0.3 m is reported in figure. Means are reported ± standard error of mean (SEM). Note that SEM of water content was smaller than 0.01. n.s. indicates the lack of significant difference. Different letters in Fig. 8 d indicate significant difference among Ψ_{pd} (power-transformed data) of Ca, Ia and Ue as tested by one-way ANOVA followed by post hoc Tukey's test. Note that during winter no measurement was possible on deciduous *C. avellana*

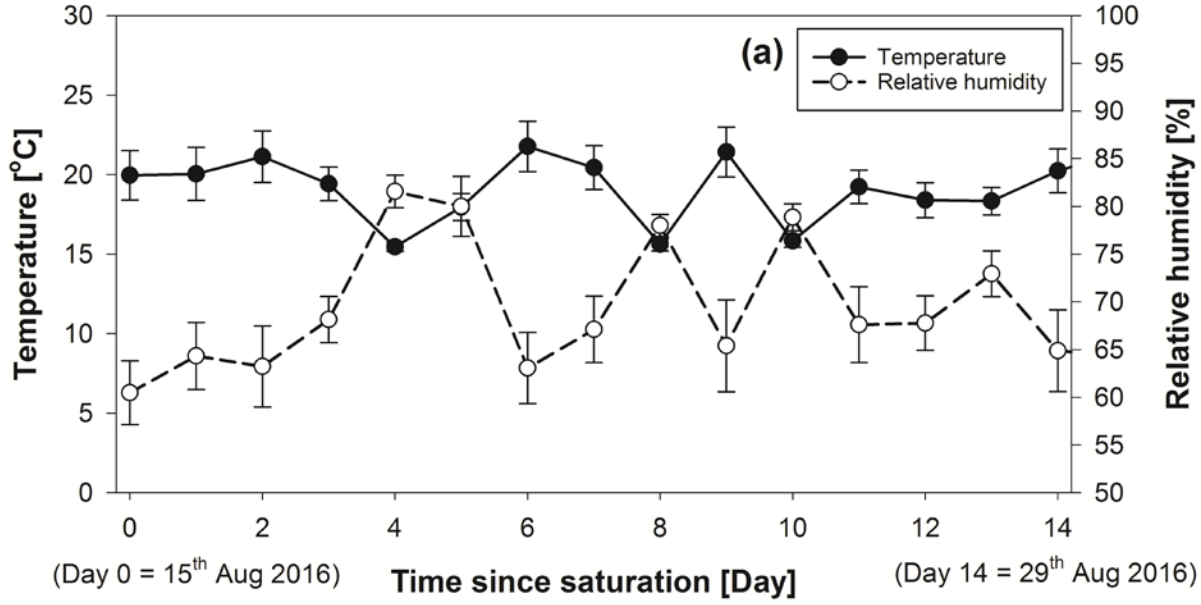
Fig. 10 Above-ground biomass of four replicate plants on June 2016 (initial biomass) and June 2017 (final biomass). Acronyms: Ca: *C. avellana*; Ia: *I. aquifolium*; Ue: *U. europaeus*. * indicates a significant difference between initial and final biomass as tested by one-way ANOVA. Means are reported ± standard error of mean

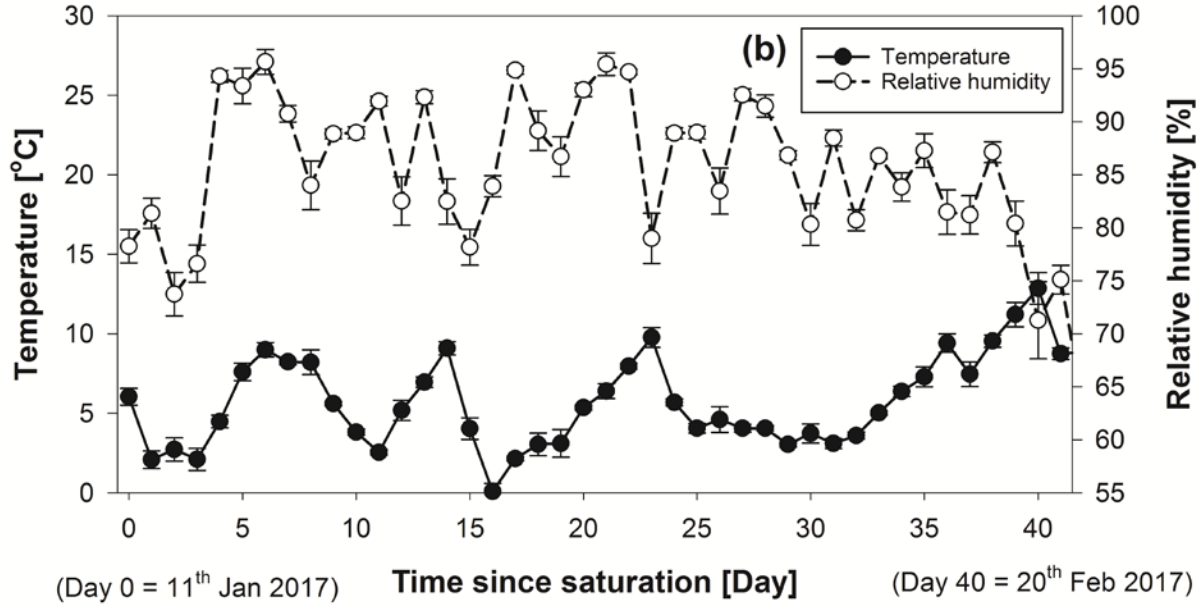
Fig. 11 Root biomass and root length density measured at different soil depths for *C. avellana* (a and d); *I. aquifolium* (b and e); *U. europaeus* (c and f). Oblique line pattern indicates the root biomass measured between soil surface and 0.15 m depth (i.e. root depth at planting)

Suppl. Fig. 1 Values of soil matric suction recorded in control and vegetated soil columns at 0.1, 0.3 and 0.7 m depth: a) Before ponding on day 11 of summer phase (August 26th); b) After ponding on day 14 of summer phase (August 29th); c) Before ponding on day 37 of winter phase (February 17th) and d) After ponding on day 41 of winter phase (February 21st). Means are reported ± standard error of mean. Different letters indicate significant penetration resistance difference among treatments (C: fallow soil (control); Ca: *C. avellana* vegetated soil; Ia: *I. aquifolium* vegetated soil; Ue: *U. europaeus* vegetated soil), as tested by one-way ANOVA followed by post hoc Tukey's test. Non-normally distributed data were log or square root transformed in the statistical analysis

961 **Suppl. Fig. 2** Percentage of root length in each diameter class between <0.1 and 5.0 mm as
962 observed in representative root samples at different depths (0.0-0.25 m; 0.25-0.50 m; 0.50-
963 0.75 m; 0.75-1.05 m). Note that the lower boundary of diameter class is included in the class
964 while the upper boundary is not. Means are reported ± standard error of mean (n= 4)

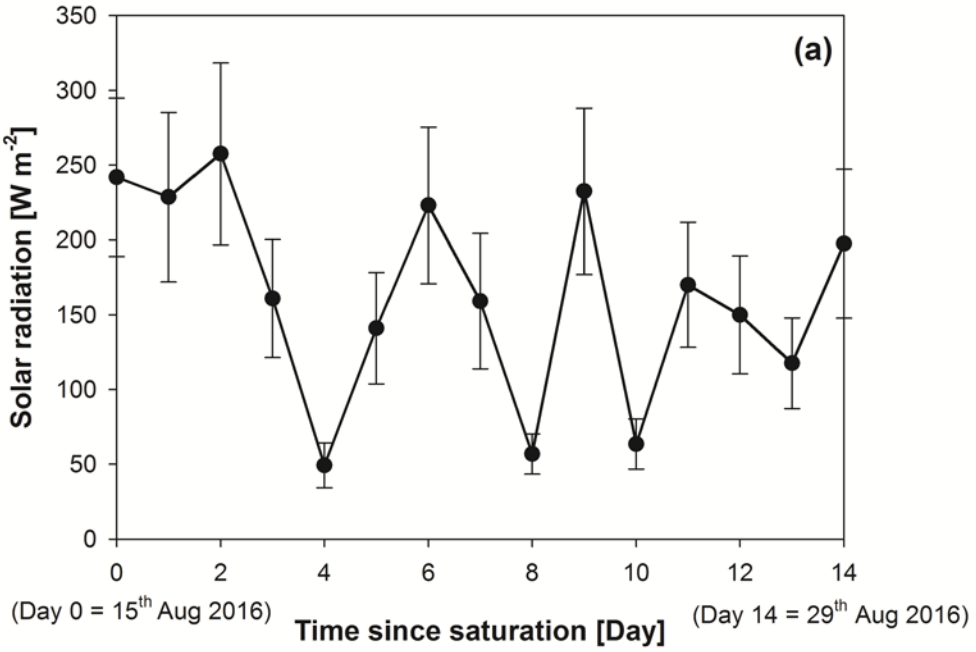
965

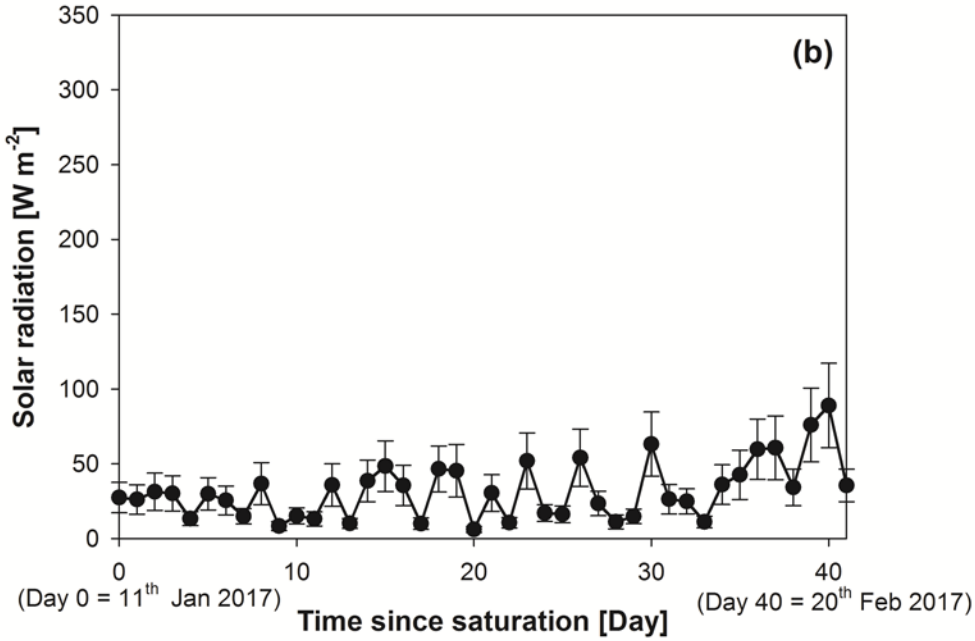

(a)
Temperature
Relative humidity
Temperature [°C]
Relative humidity [%]
(Day 0 = 15th Aug 2016)
Time since saturation [Day]
(Day 14 = 29th Aug 2016)


(b)
Temperature
Relative humidity
Temperature [°C]
Relative humidity [%]
(Day 0 = 11th Jan 2017)
Time since saturation [Day]
(Day 40 = 20th Feb 2017)

966

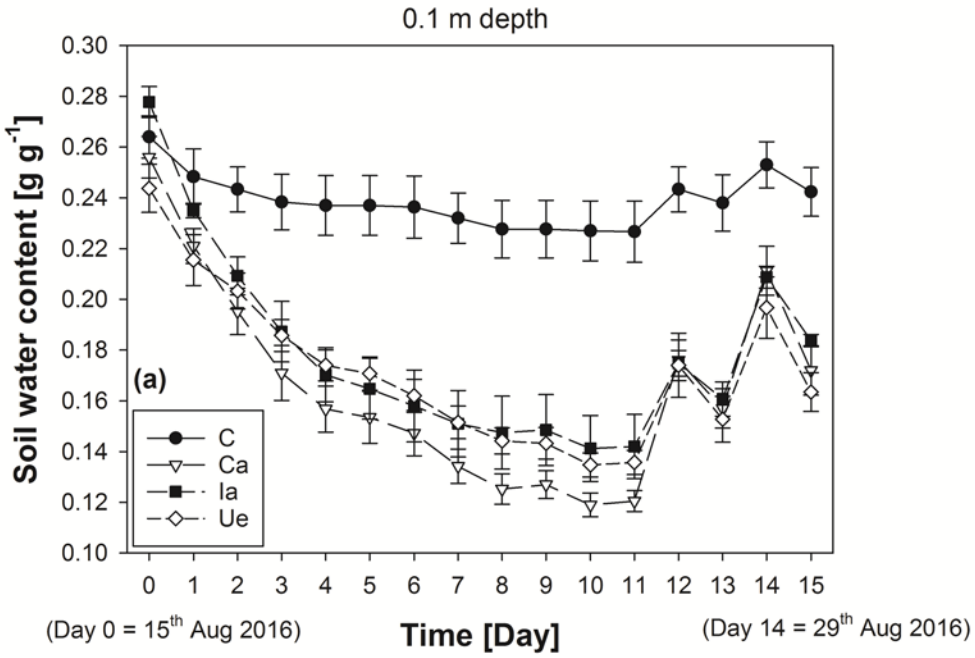
967

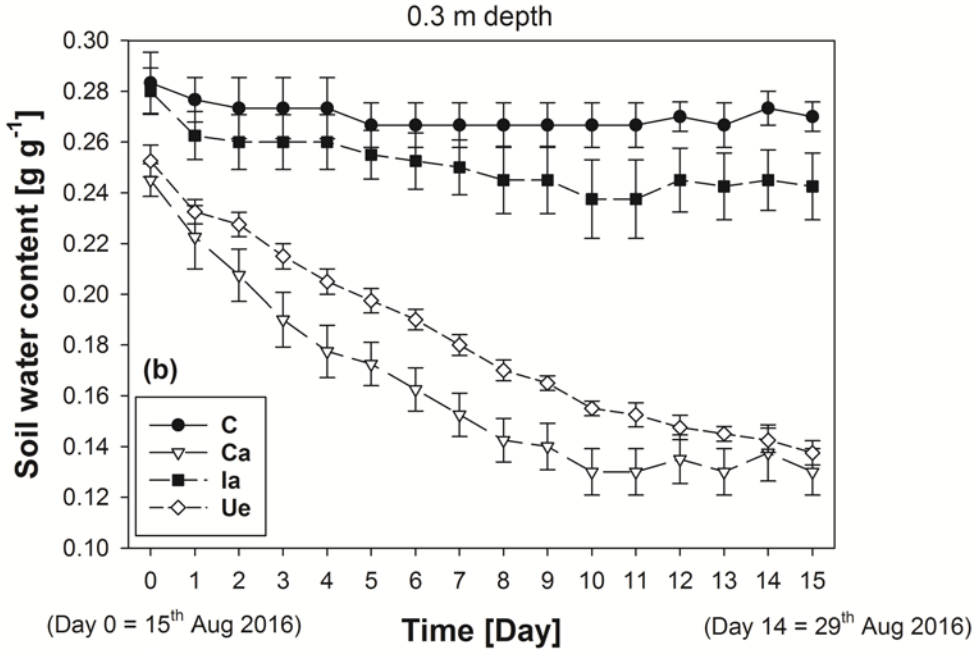

(a)
Solar radiation [W m-2]
350
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
(Day 0 = 15th Aug 2016)
(Day 14 = 29th Aug 2016)
Time since saturation [Day]


(b)
Solar radiation [W m-2]
350
300
250
200
150
100
50
0
0
10
20
30
40
(Day 0 = 11th Jan 2017)
(Day 40 = 20th Feb 2017)
Time since saturation [Day]

968

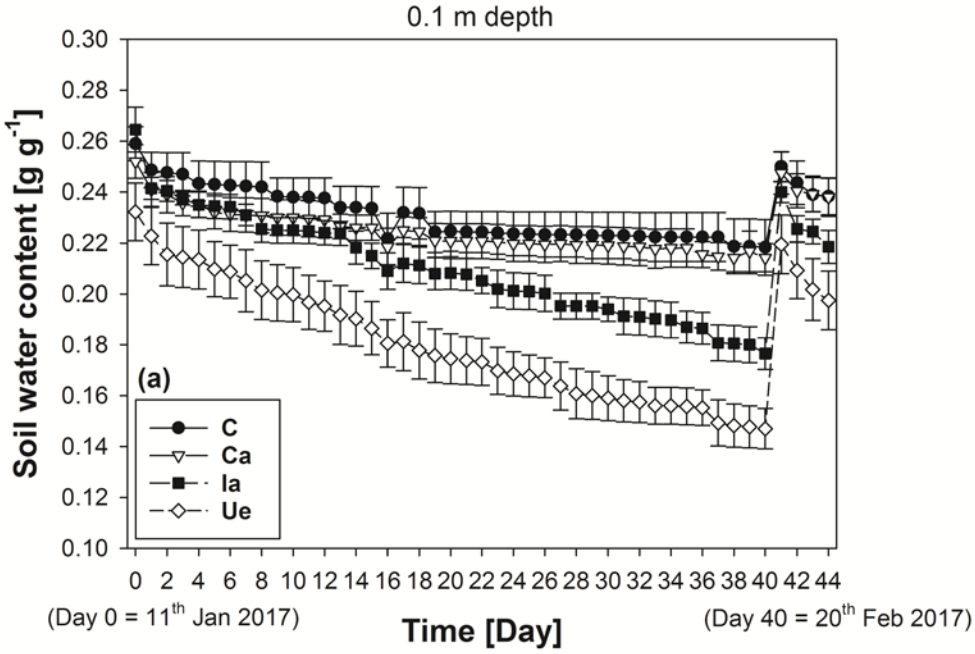
969

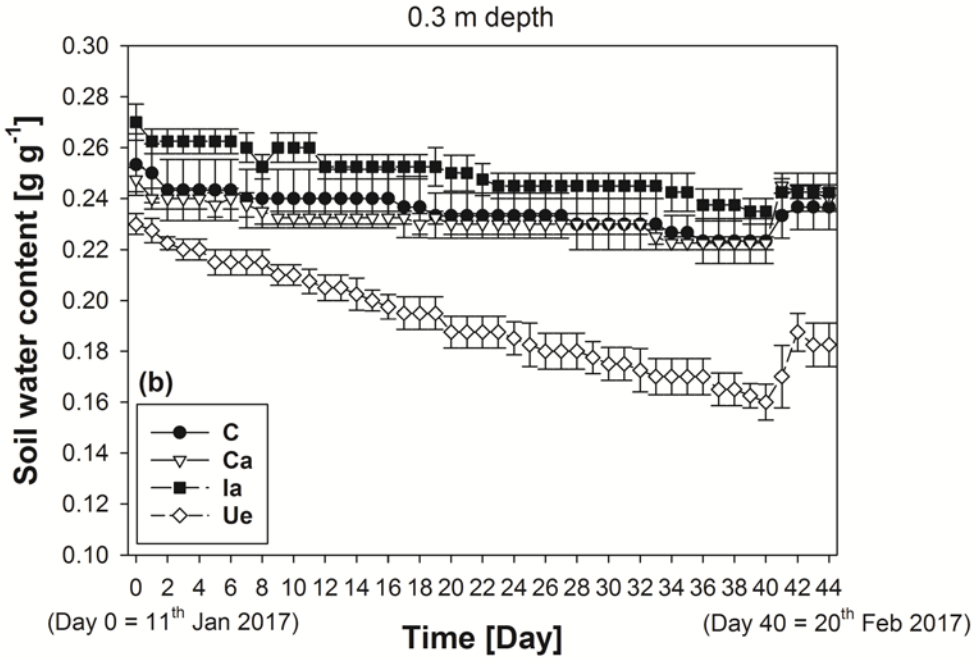

0.1 m depth
Soil water content [g g-1]
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
(a)
C
Ca
Ia
Ue
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
(Day 0 = 15th Aug 2016)
Time [Day]
(Day 14 = 29th Aug 2016)


0.3 m depth
Soil water content [g g-1]
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
(b)
C
Ca
Ia
Ue
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
(Day 0 = 15th Aug 2016)
Time [Day]
(Day 14 = 29th Aug 2016)

970

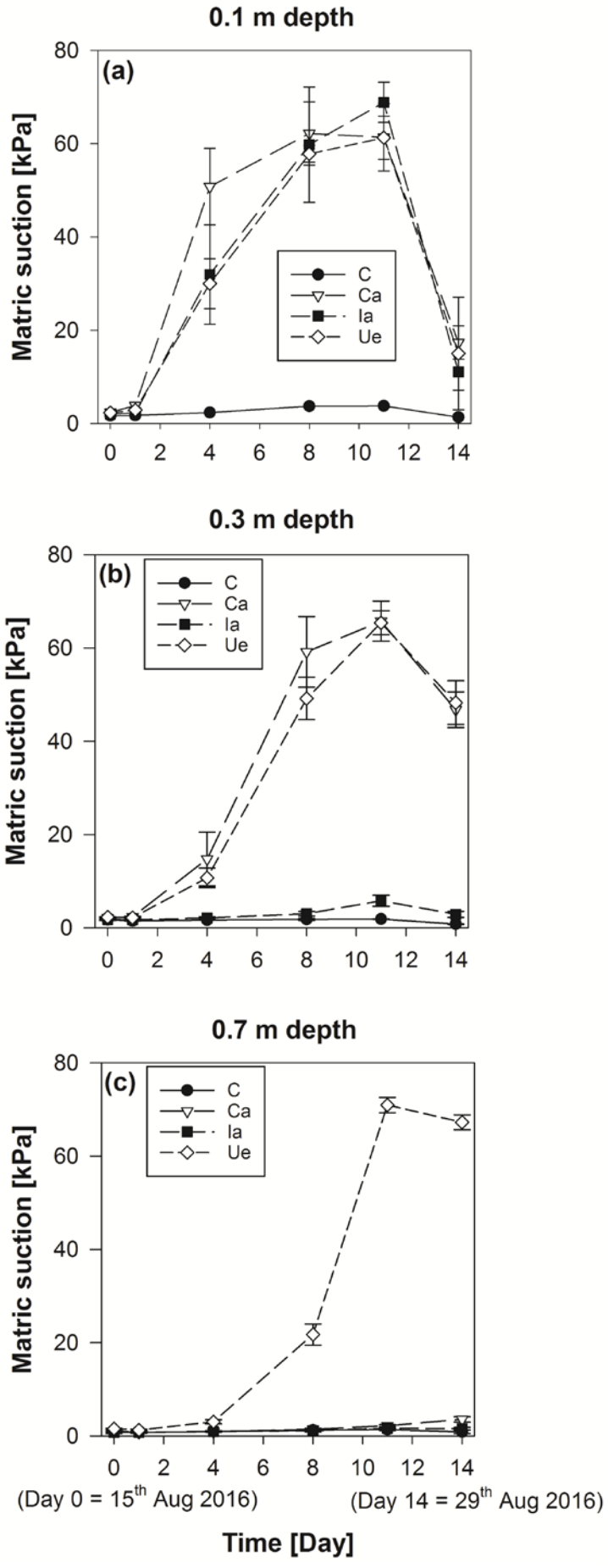
971


0.1 m depth
Soil water content [g g-1]
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
(a)
C
Ca
Ia
Ue
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44
(Day 0 = 11th Jan 2017)
Time [Day]
(Day 40 = 20th Feb 2017)

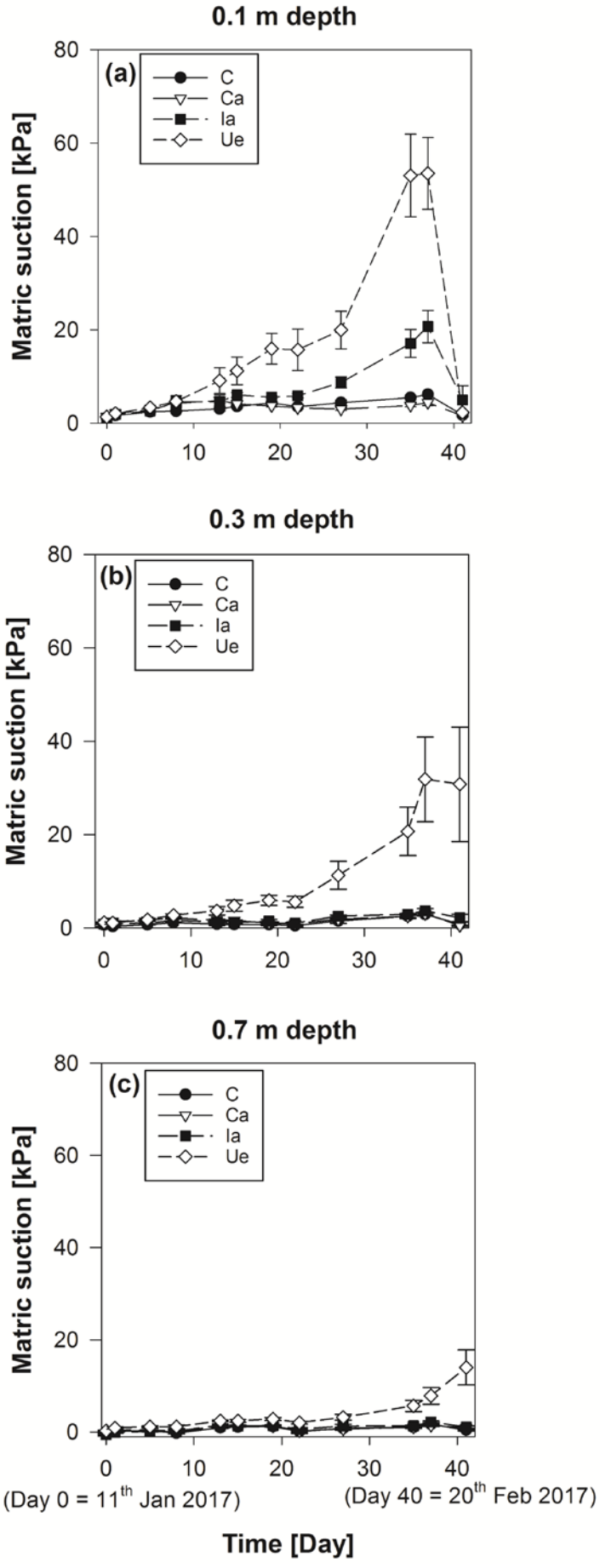

0.3 m depth
Soil water content [g g-1]
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
(b)
C
Ca
Ia
Ue
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44
(Day 0 = 11th Jan 2017)
Time [Day]
(Day 40 = 20th Feb 2017)

972

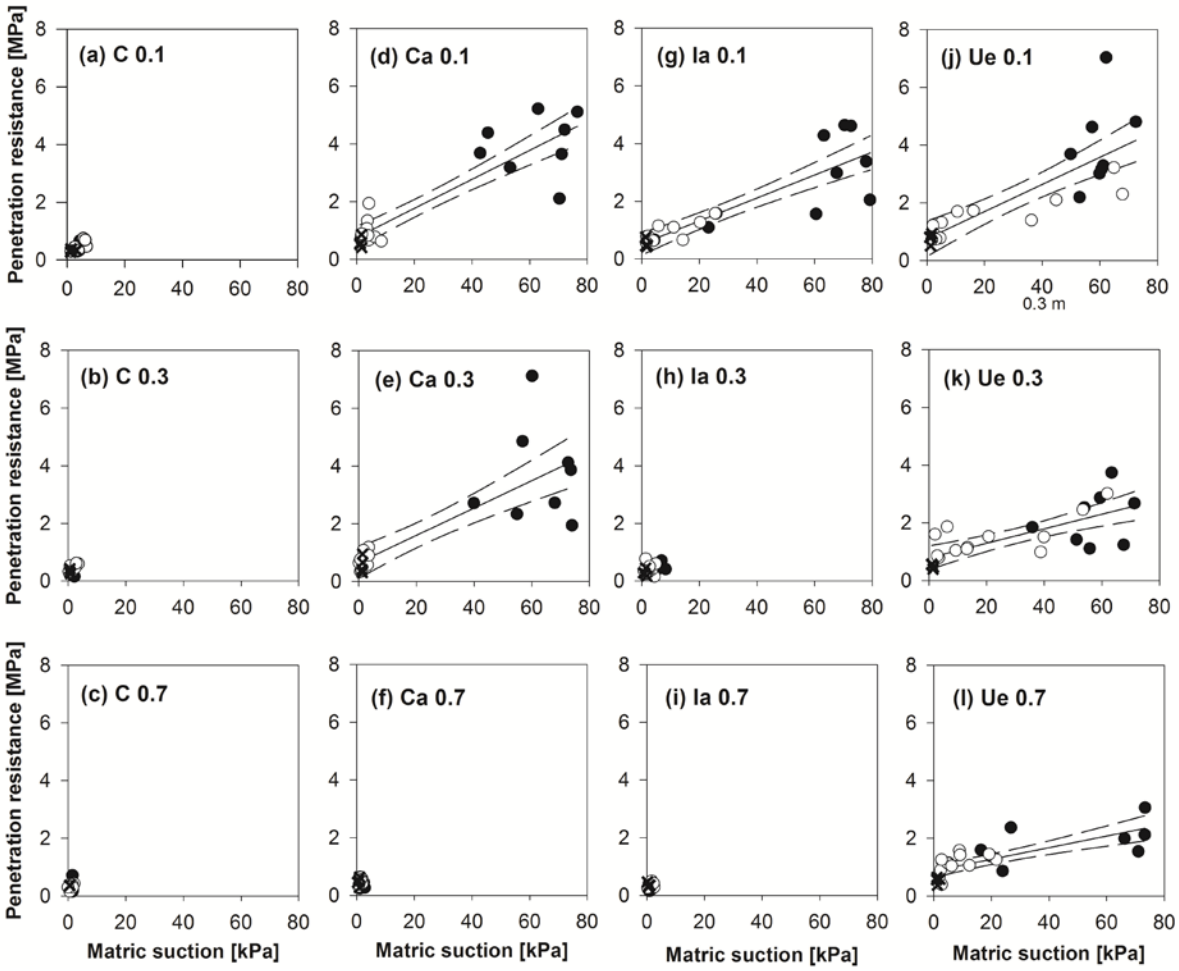
973


0.1 m depth
(a)
Matric suction [kPa]
C
Ca
Ia
Ue
0.3 m depth
(b)
Matric suction [kPa]
C
Ca
Ia
Ue
0.7 m depth
(c)
Matric suction [kPa]
C
Ca
Ia
Ue
(Day 0 = 15th Aug 2016)
(Day 14 = 29th Aug 2016)
Time [Day]

974

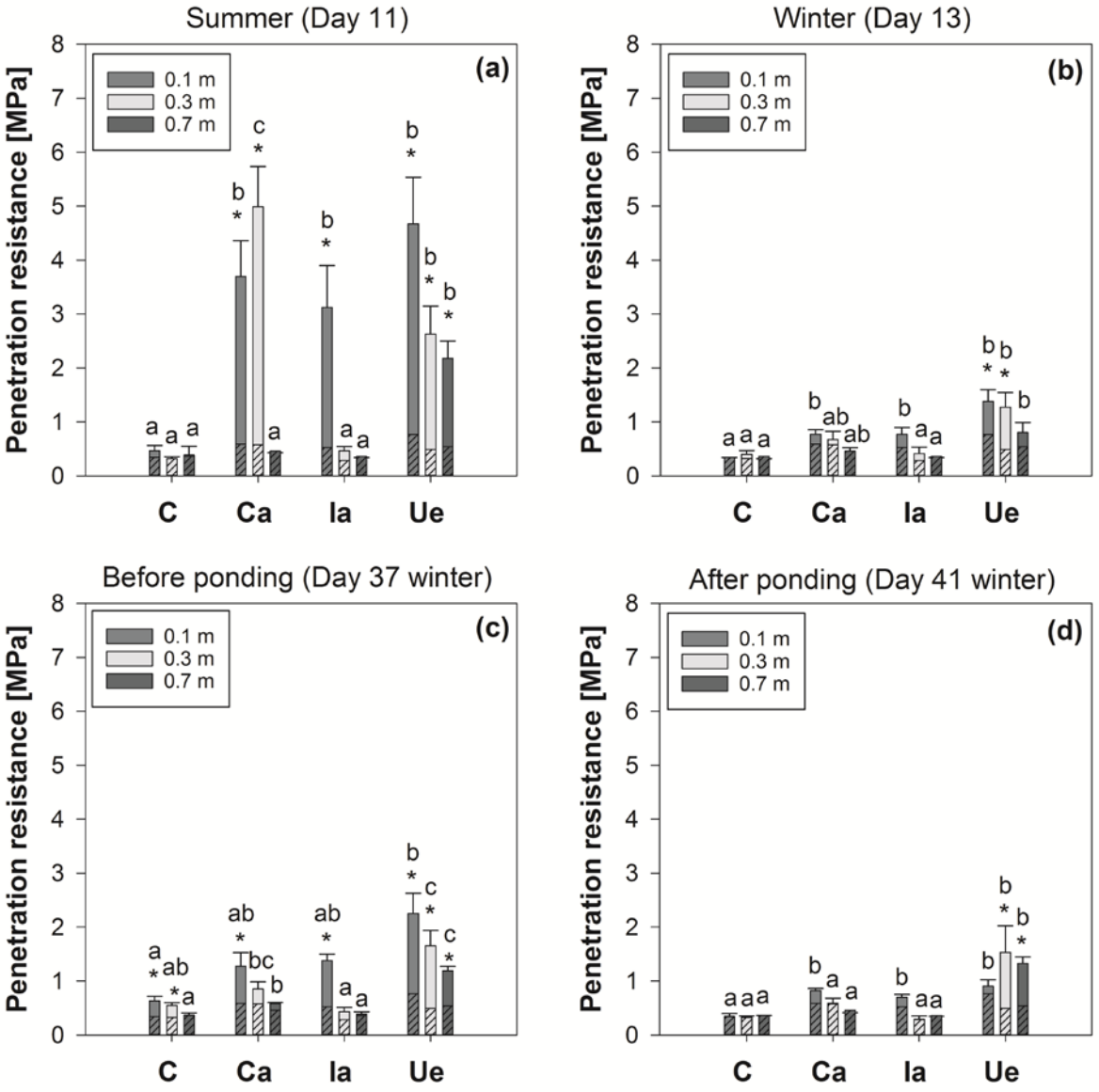

0.1 m depth
(a)
C
Ca
Ia
Ue
Matric suction [kPa]
0
20
40
60
80
0
10
20
30
40
0.3 m depth
(b)
C
Ca
Ia
Ue
Matric suction [kPa]
0
20
40
60
80
0
10
20
30
40
0.7 m depth
(c)
C
Ca
Ia
Ue
Matric suction [kPa]
0
20
40
60
80
0
10
20
30
40
(Day 0 = 11th Jan 2017)
(Day 40 = 20th Feb 2017)
Time [Day]

975


(a) C 0.1
(d) Ca 0.1
(g) Ia 0.1
(j) Ue 0.1
0.3 m
(b) C 0.3
(e) Ca 0.3
(h) Ia 0.3
(k) Ue 0.3
(c) C 0.7
(f) Ca 0.7
(i) Ia 0.7
(l) Ue 0.7
Penetration resistance [MPa]
Matric suction [kPa]

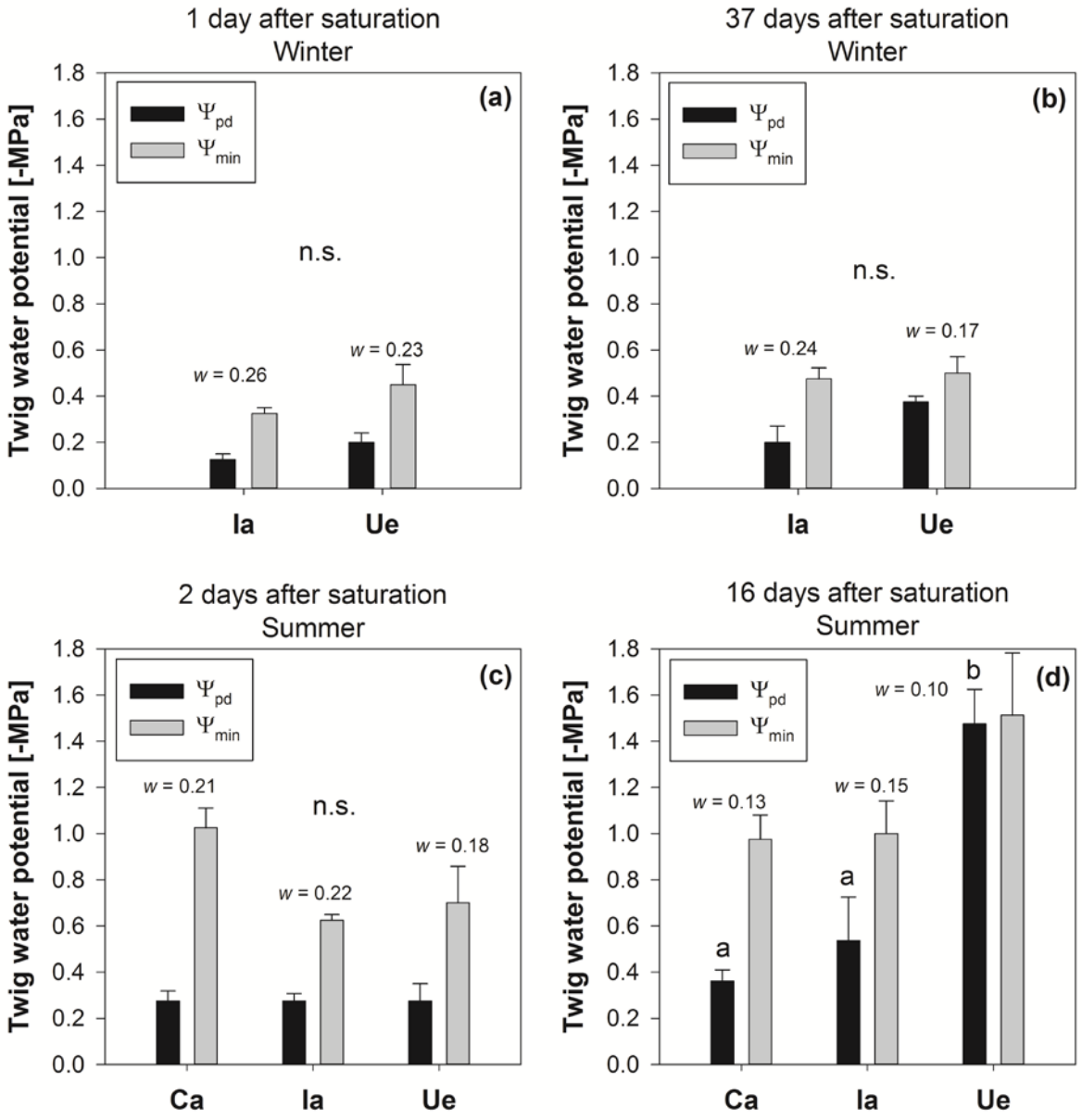
976

977


Summer (Day 11)
Winter (Day 13)
Before ponding (Day 37 winter)
After ponding (Day 41 winter)
(a)
(b)
(c)
(d)
0.1 m
0.3 m
0.7 m
Penetration resistance [MPa]
C
Ca
Ia
Ue

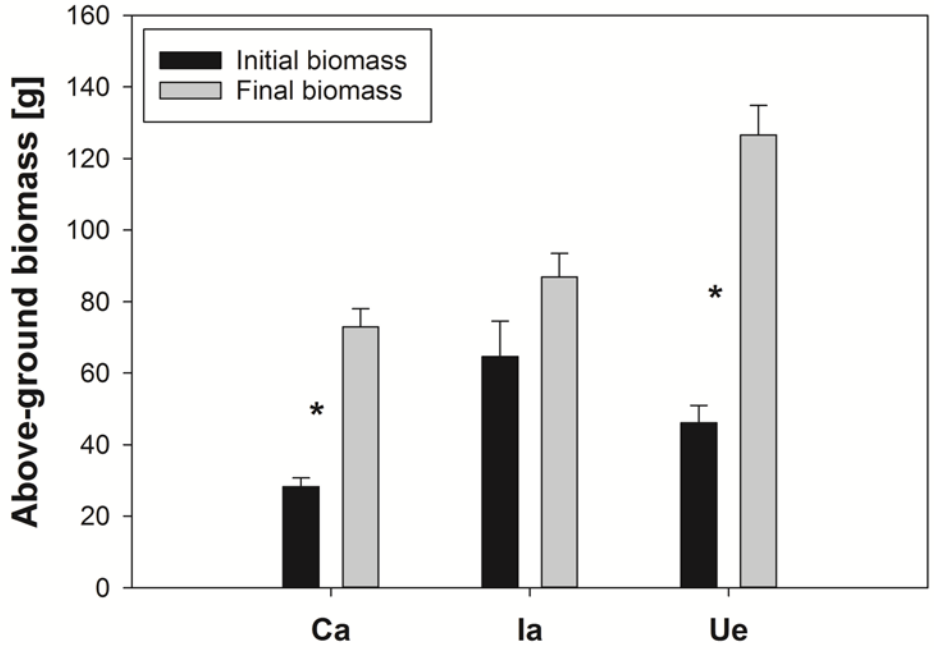
978

979


1 day after saturation
Winter
(a)
Ψpd
Ψmin
n.s.
w = 0.26
w = 0.23
Twig water potential [-MPa]
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Ia
Ue
37 days after saturation
Winter
(b)
Ψpd
Ψmin
n.s.
w = 0.24
w = 0.17
Twig water potential [-MPa]
Ia
Ue
2 days after saturation
Summer
(c)
Ψpd
Ψmin
w = 0.21
n.s.
w = 0.22
w = 0.18
Twig water potential [-MPa]
Ca
Ia
Ue
16 days after saturation
Summer
(d)
Ψpd
Ψmin
w = 0.13
w = 0.15
w = 0.10
a
a
b
Twig water potential [-MPa]
Ca
Ia
Ue

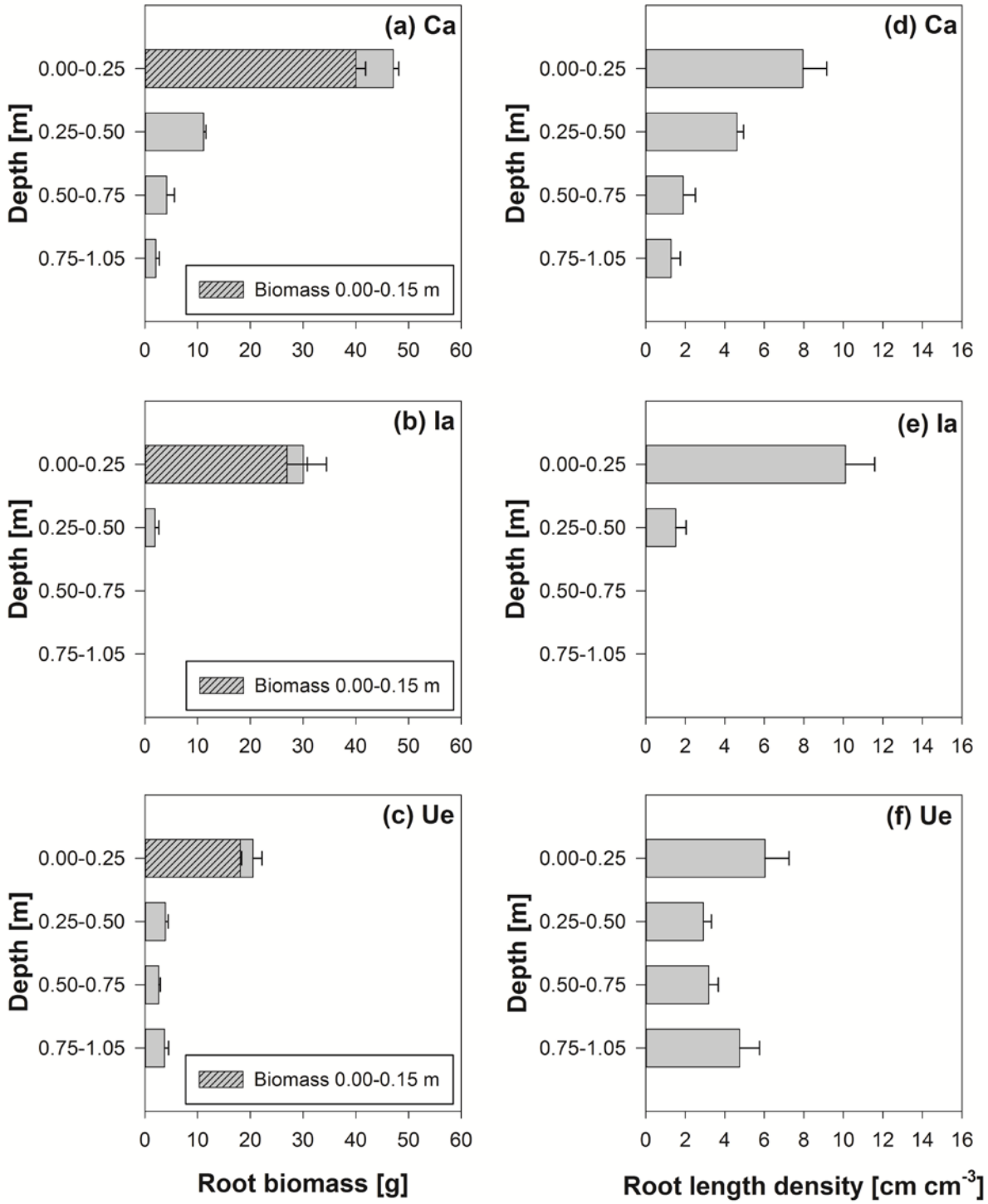
980

981


Above-ground biomass [g]
160
140
120
100
80
60
40
20
0
Initial biomass
Final biomass
*
*
Ca
Ia
Ue

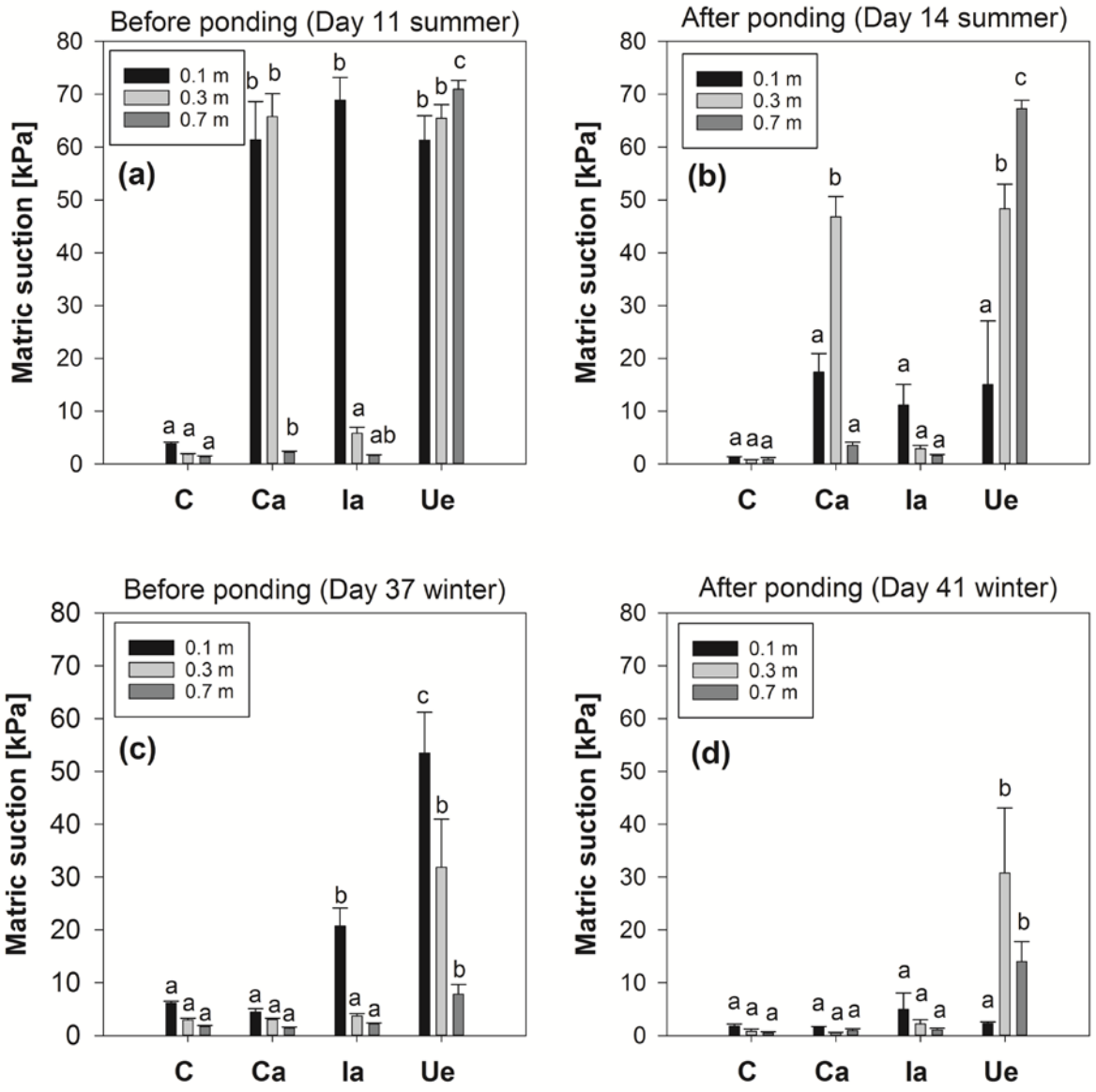
982

983


(a) Ca
(b) Ia
(c) Ue
(d) Ca
(e) Ia
(f) Ue
Depth [m]
0.00-0.25
0.25-0.50
0.50-0.75
0.75-1.05
Biomass 0.00-0.15 m
0 10 20 30 40 50 60
0 2 4 6 8 10 12 14 16
Root biomass [g]
Root length density [cm cm-3]

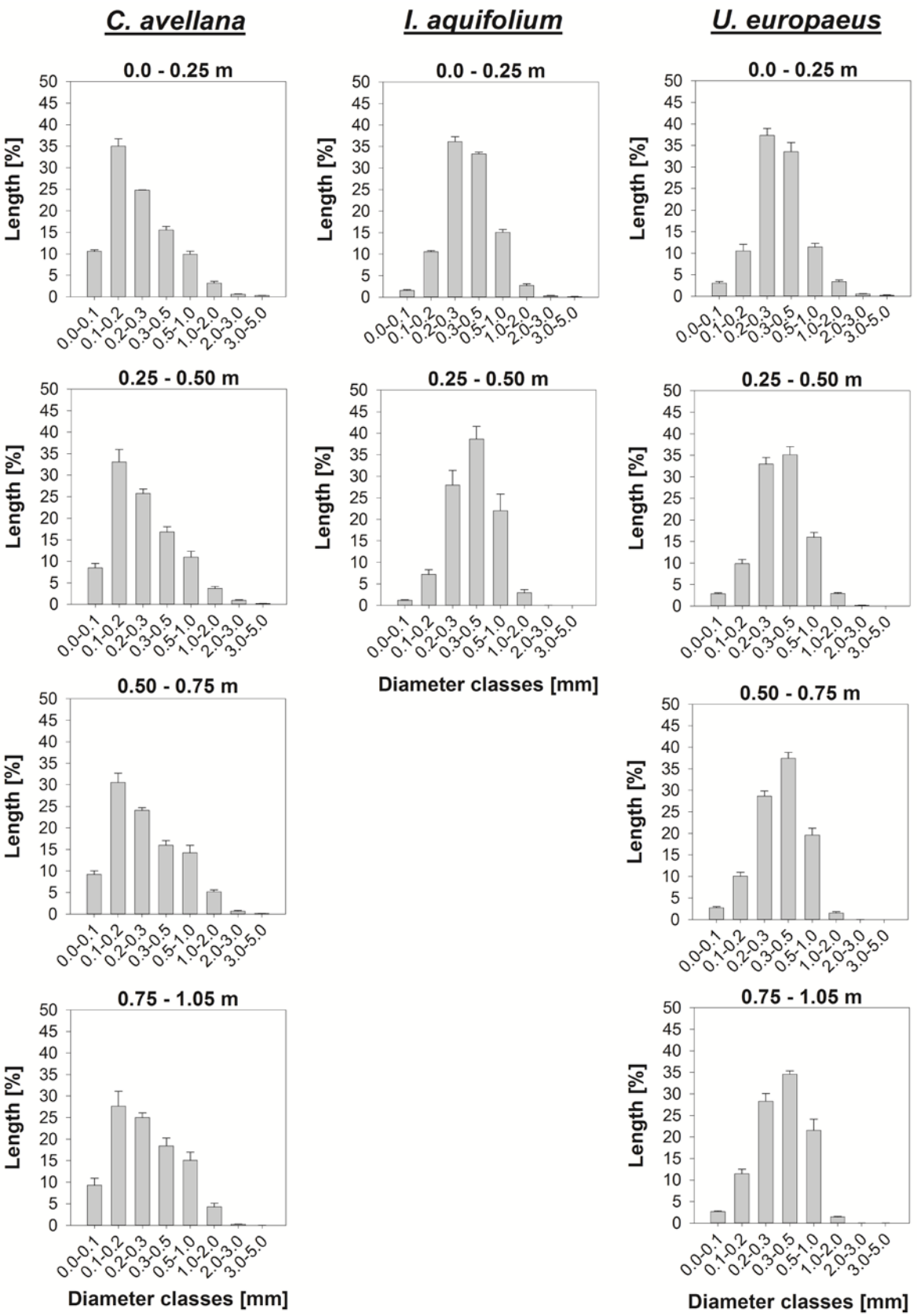
984

985


Before ponding (Day 11 summer)
After ponding (Day 14 summer)
Before ponding (Day 37 winter)
After ponding (Day 41 winter)
Matric suction [kPa]
0.1 m
0.3 m
0.7 m
(a)
(b)
(c)
(d)
C
Ca
Ia
Ue

986

987


C. avellana
I. aquifolium
U. europaeus
0.0 - 0.25 m
0.25 - 0.50 m
0.50 - 0.75 m
0.75 - 1.05 m
Length [%]
0 5 10 15 20 25 30 35 40 45 50
0.0-0.1
0.1-0.2
0.2-0.3
0.3-0.5
0.5-1.0
1.0-2.0
2.0-3.0
3.0-5.0
Diameter classes [mm]

988